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# AURORAL ELECTRON DRIFT AND PRECIPITATION: CAUSE OF THE MANTLE AURORA

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## ABSTRACT

Data from the Auroral Particles Experiment on OGO-4 have been analyzed to determine the properties of the band region of low energy electron precipitation in the late morning hours. The existence of this precipitation is consistent with a scheme involving a release of a body of electrons on closed magnetic field lines in the vicinity of midnight at the time of a magnetospheric substorm, with a subsequent drift in local time through the morning hours at least as far as noon. While drifting the electrons encounter a strong pitch angle diffusion mechanism which precipitates them into the atmosphere to produce the mantle aurora. This mechanism seems to exist independent of substorm magnetic activity. The diffusion coefficient must be larger than $10^{-3}$/second, and the resulting lifetime of the electrons is about $6 \times 10^{3}$ seconds. The energy density of the source electrons in the midnight region would not be unreasonably large if the source is in the cusp.

## INTRODUCTION

Measurements from satellites of precipitating low energy electrons have established the existence of two fairly distinct regions of precipitation during the late morning hours. The first, lower latitude region, is characterized by relatively hard, isotropic radiation, not displaying much structure in its latitude profile. It has been labeled the "hard day zone" by Sharp and Johnson (1968), "the auroral zone" by Burch (1968), and the "band region" by Hoffman (1969). The second, higher latitude region, is distinguished by a nominally very soft electron spectrum, and exhibits a highly structured profile in the counting rate from a low energy electron detector. It has been described by the terms "soft day zone", the "soft zone", and the "burst region" by the afore mentioned experimenters.

Data from the OGO-4 Auroral Particles Experiment have been analyzed to determine further properties of the lower latitude region of precipitation, with special interest in the origin or source of the precipitating electrons, and the association of these electrons with auroral activity in the late morning hours.

This analysis, which also utilized ground station magnetic records as an indicator of magnetic activity, suggests that the existence of this electron precipitation is consistent with a scheme involving a release of a body of electrons on closed magnetic field lines in the vicinity of midnight at the time of a magnetospheric substorm, with a subsequent drift in local time through the morning hours at least as far as noon. While drifting the electrons encounter a precipitation mechanism which causes a loss of the electrons into the atmosphere.

In searching for an auroral optical phenomenon which could be associated with these precipitating electrons, we find that the auroral type defined as the "mantle aurora" by Sandford (1964, 1968) is consonant with our particle observations. This aurora, measured photometrically at the λ3914 and λ5577 emissions, is a relatively steady, diffuse, subvisual aurora covering a large area of the sky, and occurring in the absence of discrete auroral forms as recorded on ground level all-sky camera photographs (Gowell and Akasofu, 1969). The region of luminosity exists in a zone at nearly constant magnetic latitude from the midnight region through the morning hours to noon. Sandford (1968) found that on integrating the emissions over the entire high latitude region, the mantle auroral emissions were on the average the predominant optical phenomenon during solar maximum, giving rise to the majority of all auroral emissions, while at solar minimum such emissions dropped to about half the emissions. This suggests that the mantle aurora region of space is an important sink for energy from the magnetosphere.

Unfortunately the data from the OGO-4 experiment does not allow u to conclusively prove the described sequence of events of particle release, drift, precipitation and auroral emissions due to operational criteria associated with the experiment (see Experiment and Operational Criteria, below) as well as problems inherent in interpreting data acquired from a low altitude polar orbiting satellite. Instead the consistency with this model will be displayed in the following manner:

1. We will show that electrons do not precipitate in copious quantities in the region of local midnight at auroral latitudes except during

magnetic activity in that sector, especially substorm activity. We restate this as auroral electrons display their existence in the midnight region only during substorms. We will later conclude that at the time of substorms the electrons begin their eastward drift in magnetic local time. Because the particle measurements were performed by an experiment on a low altitude satellite the only indication of the existence of electrons on a magnetic field line is the observation of precipitating or low altitude mirroring particles. There is no knowledge of the possible existence on a line of force of electrons all of whose mirror points lie above the satellite (a condition equivalent to there being no precipitation mechanism). Therefore, there is no discussion as to when the electrons are accelerated or are injected onto auroral field lines near midnight. It is only in the context of measuring electrons at low altitudes that we use the word "existence".

2. Next we will show that during the morning hours, and more clearly near noon, the electrons do not precipitate or exist at latitudes characteristic of the mantle aurora ($68^{o}$ to $78^{o}$) at the time of a substorm.

3. Finally we will provide examples of precipitation of electrons in the late morning sector some hours after the magnetic activity near midnight. This delay in the appearance of electrons in the late morning hours is the time for these electrons to drift from midnight to noon. The sequence of the existence of electrons

at midnight and the late morning hours is the basis for the conclusion that the electrons commence their drift at the time of the substorms.

4. To associate these electrons with the mantle aurora, we will show that the energy influx of the observed electrons is sufficient to produce the emissions measured by Sandford, and the spatial distribution of the precipitating electrons is similar to that of the mantle aurora.

## EXPERIMENT AND OPERATIONAL CRITERIA

Details of the Auroral Particles Experiment have been thoroughly described by Hoffman and Evans (1967) and pertinent aspects by Hoffman and Evans (1968). Briefly, the experiment contains an array of eight detectors, each comprised of an electrostatic analyzer for species and energy selection and a Bendix channel electron multiplier as the particle detector. Four of the detectors always point radially away from the earth ($0^{o}$) and measure electrons in narrow (about $\pm$ 15%) energy bands around 0.7, 2.3, 7.3 and 23.8 kev. Three others are positioned $30^{o}$, $60^{o}$, and $90^{o}$ to the earth-spacecraft radius vector, and all measure electrons in an energy band at 2.3 kev.

Because this experiment was devised at the time when the fatigue characteristics of channel multipliers were relatively unknown, the experiment was not allowed to operate continuously in orbit. Data acquisition was initiated via ground command usually as the satellite was approaching the auroral zone. This command initiated a 13½ minute timer controlling the high voltage on the detectors which allowed data to be collected when the satellite passed over the auroral zone, crossed the polar cap, and again crossed the auroral zone. The necessary proximity of a ground station to initiate the acquisition period caused data to be acquired only during certain portions of the day, and seldom were more than three successive passes obtained.

Data acquisition for the experiment was further complicated and compromised by orbital operations requirements of the spacecraft, especially pertaining to spacecraft attitude control and on-board tape recorder dumps, as well as by the use of several different spacecraft data acquisition formats, some of which did not interrogate any or all of the experiment.

The satellite was launched on July 28, 1967, into a low altitude polar orbit having an apogee of 908 km, a perigee of 412 km, an inclination of $86^{o}$ and a period of about 98 minutes.

## DATA DISPLAY

In the analysis of data acquired from the experiment when the satellite was passing through the high latitude region during the morning and noon hours, the two precipitation regions were identified in the following manner: the lower latitude band region is most distinguishable in the output of the 7.3 kev electron detector, which produces a relatively unstructured counting rate profile of moderately intense fluxes (> $10^5$ electrons/$cm^2$-sec-ster-kev). The higher latitude burst region is characterized by large, rapid variations in the counting rate of the 0.7 kev detector, although at such times the 7.3 kev detector may also respond in coincidence. Since the two regions may somewhat overlap, the band region is defined as that precipitation region of 7.3 kev electrons not in coincidence with structured 0.7 kev electron precipitation. This band region is the primary region of interest in this paper.

The display of data in the first eight figures has the following common features. Data are averaged over about a 10 second period of accumulation independent of the bit rate from the satellite. The orbit of the satellite is shown in magnetic local time (MLT), invariant latitude ($\Lambda$) coordinates with a tick mark at each minute. The locations of pertinent magnetic observatories are also marked for the time periods of the experiment data acquisition. The time scale for the magnetograms, in UT, is immediately above the tracings. The small letters M or N above the vertical arrows on the magnetograms indicate when the observatory passed local magnetic midnight or noon. The H or X by each magnetogram scale refers to the horizontal or northward component of the field, respectively. The base line on the magnetograms was arbitrarily chosen, since only the occurrence of a disturbance is of interest.

## 1. Midnight Precipitation.

The purpose of Figure 1 is to show that electrons of 7.3 kev energy do not precipitate with any appreciable intensity in the midnight sector during magnetically quiet periods. The 7.3 kev detector was measuring fluxes less than $10^5$ north of $71^o$ latitude and much less than this below $66^o$. Three bursts in coincidence with the 0.7 kev electrons occurred between 66° and 71°, more specifically at 66½°, 69° and 71°. The average flux of 7.3 kev electrons between 66° and 71° latitudes was about 2.6 x $10^5$. Note the extremely quiet magnetograms from Murmansk (USSR) and Tromsø (Norway) when these observatories were also near midnight.

In contrast to the data in Figure 1, Rev. 931 in Figure 2 displays large intensities of 7.3 kev fluxes near midnight during a substorm. From 60° to 65° the fluxes exceeded $10^7$, and at higher latitudes the intensities in two bursts exceeded 2 x $10^7$. As indicated in the lower half of the figure this data was acquired during a substorm observed at Kiruna (Sweden), when this observatory was located a few minutes before magnetic midnight (see the small polar plot in Figure 2).

Of course these observations are consistent with the results of sounding rocket measurements of auroral particle precipitation at night (for reviews, see Evans, 1967; Whalen and McDiarmid, 1969), and are only shown as part of a complete and self-consistent model of the source of late morning precipitating electrons.

2. Late Morning Precipitation During Substorms.

We next show three examples of no appreciable fluxes of precipitating electrons near local noon while magnetic substorms were in progress in the midnight sector.

Using data from a noontime pass during the same substorm as the previous example, we see during Rev. 933 shown in Figure 2 very small fluxes of 7.3 kev electrons in the latitude interval 68° to 78°. In fact most of the measurable precipitation is in coincidence with bursts at 0.7 kev at latitudes $70^{\circ}$, $74^{\circ}$ and $77^{\circ}$, and therefore does not correspond to our definition of a band region. This data was acquired almost eight hours after the onset of the abnormally long substorm or overlapping series of substorms at Kiruna.

The example in Figure 3 is not as convincing as the previous example, because small fluxes at 7.3 kev were observed from experiment turn-on at 2341 to 2342 when the burst region was entered. However, these fluxes of about $3 \times 10^5$ were an order of magnitude weaker than those observed at this local time during precipitation events, as will be shown. Note that this pass, Rev. 771, occurred about five hours after the onset of the substorm.

The final example of this type (Figure 4) shows the lack of precipitating electrons in the very early afternoon hours during a large substorm. During Rev. 1352 the flux of 7.3 kev electrons did not reach $10^5$ from latitude $73^{\circ}$ to the highest latitude reached (from about 1037 to 1041 UT), while during Rev. 1353 the flux was less than $2 \times 10^5$ from $70^{\circ}$ to $81^{\circ}$ (1212.5 to 1218 UT) except for a burst in coincidence with the large 0.7 kev precipitation at 1214 UT. The data from these two revolutions was acquired during a large substorm apparent in the College (Alaska) magnetogram when this observatory was near local midnight.

Towards the end of these two segments of data, when the satellite passed through the auroral zone in the early evening hours local time, large fluxes of both 0.7 and 7.3 kev electrons were encountered. These data show the wide extent in local time from which the 7.3 kev electrons can originate during a substorm.

These three examples demonstrate that there is no significant diffuse source or region of precipitating electrons in the late morning hours at latitudes appropriate to the mantle aurora during magnetospheric substorms.

3. Late Morning Precipitation After Substorms.

Finally we show a set of four examples, each with increasing complexity, of electrons precipitating during the late morning hours, but appearing well after the onset of a substorm in the midnight region.

The event shown in Figure 5 involved a substorm commencing about 1330 UT on October 11, 1967, as observed at College (Alaska) when the observatory was near local early morning hours. The satellite pass some $6\frac{1}{2}$ hours later at about 10 hours MLT, Rev. 1108, encountered fluxes of 7.3 kev electrons exceeding $10^6$ at latitudes from $68^{\circ}$ to $75^{\circ}$. At about $73^{\circ}$ the burst region began, and was evident even in the 7.3 kev detector output between $76^{\circ}$ and $84^{\circ}$ latitudes. During this pass the Kiruna observatory at local midnight indicated no magnetic activity.

The next example of this type (see Figure 6 magnetograms) had an initiating substorm commencing between 11 and 12 hours UT on October 23, 1967, and again observed at College. Data were acquired from a series of four passes commencing about 6 hours after the onset of the substorm and occurring at about 09 hours MLT. During these passes the Murmansk observatory was rotating in local time through the midnight hours and measured some small magnetic activity during the times of the first two passes, 1242 and 1243 (see the bottom of Figure 6).

The electron flux measurements during the morning portion of the four passes are plotted in the first, third, fourth and fifth panels in the upper portion of Figure 6. For Rev. 1242, data from only the highest latitude portion of the band region were acquired from 72° to 74½° latitude and centered around 1810 UT. For the next three revolutions the burst and band regions only slightly overlapped, so the 0.7 kev fluxes are not plotted. In panel 2 the data are plotted from the midnight portion of Rev. 1242 during the small magnetic disturbance seen at Murmansk, and indeed appreciable fluxes of both 0.7 and 7.3 kev electrons were measured.

A striking observation of these morning precipitating electrons is the identical maximum flux of about $3 \times 10^6$ during all four passes, which extended in univeral time over a period of five hours. We use this observation as evidence that particles in the late morning precipitation originated near midnight at the time of the substorm around 1200 UT, rather than associating them with the disturbance seen at Murmansk, since this later activity lasted only through the first two of the four passes. Since we know that electrons exist in the midnight region only at the time of magnetic activity in the auroral zone, these electrons must have spent the time between the substorm when they were presumably near midnight and their precipitation in the late morning hours drifting in local time. Since these particles drift they must be on closed field lines, so it is on this basis that we conclude that electrons are released on closed field lines in the region of midnight during substorms and subsequently drift through the morning hours.

The third example of this type, shown in Figure 7, is similar to the second in that a new magnetic disturbance occurred during some of the noontime passes. (Because the apparent drift time from midnight to late morning hours for electrons of these low energies is at least two times the average time between substorms, it is very difficult to obtain clear examples of morning precipitation without intervening magnetic activity at midnight, especially when the additional criteria of the satellite and experiment operational constraints are added, as well as the requirement of proper locations of magnetic observatories.)

The initiating substorm commenced at 13 hours UT on October 3, 1967, as recorded by the College observatory (see magnetograms in Figure 7), and lasted for over two hours. The Murmansk and then the Leirvogur observatories moved through the midnight region during the time period between revolutions 990 through 993. Their records indicate some magnetic disturbance, especially just prior to revolution 990, but by revolution 993 the Leirvogur tracing was very quiet. The electron data from the midnight portions of the passes, plotted in panels 1 and 3 of Figure 7, also indicated this decreasing activity in the midnight region. Rev. 990, plotted in the first panel, showed reasonable fluxes of both 0.7 and 7.3 kev electrons from 75° down to 64° at about 2052 UT. However, during Rev. 991 shortly after midnight local time and at about 2230 UT the intensities at 7.3 kev plotted in the third panel were considerably depressed between latitudes 75° to 67° compared to the fluxes observed in this section on the previous pass, indicating, like the magnetograms, a decreasing activity.

In spite of this decreasing activity at midnight, data from revolutions 991, 992 and 993 near noon (plotted in panels 2, 4 and 5) show continuous precipitation in the latitude interval 68° to 76°. In fact, of the three revolutions, the last has the largest integrated flux across the entire precipitation region, and this occurred when the activity at midnight was a minimum. Thus again it appears that late morning precipitation does not occur simultaneous with activity in the midnight region, but rather occurs some hours subsequent to magnetic activity in this region.

The final example (Figure 8) is again a sequence of events. The initial observations of precipitating electrons during the late morning hours occurred during substorm activity at midnight. However, electrons apparently originating during this activity were encountered several hours later precipitating near noon.

As recorded at College and Barrow (Alaska), the associated initiating magnetic activity in the midnight region from about 1100 to 1500 UT on February 5, 1968, was not in the form of classical substorms (see magnetograms in Figure 8), but instead there was a period of magnetic disturbance. The first electron observations during the late morning hours occurred at 2017 UT (Revolution 2833, plotted in panel 1 of Figure 8) in which appreciable 7.3 kev electron fluxes were measured from about 74° down to 67°. While Murmansk and Kiruna at midnight showed some magnetic variations during this acquisition period, a substorm did not commence until a few minutes after the pass. On the next revolution, 2834 (panel 2), precipitating electrons with fluxes greater than $10^6$ at 7.3 kev were measured at latitudes below 68° at experiment turn-on at 2145 UT just after midnight

MLT, and almost over Murmansk, as shown in the polar plot above this panel. Surprisingly the magnetic field at Murmansk and Kiruna had almost returned to normal during this pass. Towards the end of the data acquisition period on this revolution moderate fluxes of electrons at 7.3 kev were again observed in the morning hours from 75° down to 67°. In the following revolution, number 2835 shown in the third panel, a similar behavior appeared both in the portion of the pass post-midnight and during the morning hours. The next revolution, 2836, had more fragmented precipitation post-midnight, but again similar fluxes at 7.3 kev during the morning hours even though at this time the magnetic field near local midnight at Leirvogur was quiet.

Several hours later data were acquired from a midnight to noon pass (Rev. 2839, plotted in the last panel of Figure 8) when the magnetic activity at midnight, now measured by Great Whale River and Churchill (Canada), had completely subsided. Particle precipitation was almost non-existent in the midnight portion of the pass from 0548 to 0551 UT, but the high latitude boundary of the local noontime precipitation region was observed before data acquisition ceased at 0601 UT.

Again, with this series of passes there appears a lack of correlation between the occurrence and intensity of electron precipitation in the late morning hours and simultaneous magnetic conditions near midnight, whereas the existence of earlier magnetic activity near midnight seems to be a necessary condition for morning hour electron precipitation.

4. Energy Spectrums

Only four point energy spectrums of near $0^{o}$ pitch angle particles could be obtained from the experiment. In general, the spectrums may be grossly characterized as "knee-type" (Figure 9), that is, the slope between 2.3 kev and 7.3 kev is less than above 7.3 kev and below 2.3 kev. Spectrum labeled "2", however, has a constant $E^{-1}$ slope. Unfortunately the energy resolution of the experiment was not sufficient to distinguish structure such as peaks in the spectrum in the kev energy range, such as have been observed in breakup and pre-breakup aurora (Evans, 1969).

Under the assumption that the precipitating electrons were isotropic over the upper hemisphere at all energies (see Pitch Angle Distributions, following) the energy spectrums of the energy influx were calculated for the three spectrums in Figure 9 and are plotted in Figure 10. The knee-type spectrums show peaks in the energy input at the 7.3 kev detector. An estimate of the total energy input in the range 0.7 to 25 kev results in 6, 5 and 2 ergs/cm$^2$-sec for the three spectrums, respectively. With a loss cone of about $60^{o}$ to $70^{o}$, about one-half to two-thirds of this energy is lost into the atmosphere.

The energy spectrum during revolution 1108 (Figure 9) was previously published (Hoffman, 1969, Figure 3, labeled "Band"), and was used by Rees (1970) to examine the effect of these bombarding fluxes on the atmosphere. One of his results was the calculation of the integrated column emission rates for the $\lambda 3914$ and $\lambda 5577$ lines for this spectrum of incident electrons and he obtained 0.60 and 0.43 kR respectively, about the levels observed by Sandford (1964, Figures 7 and 9) for $K_p$ of 1 to 2. The spectrums measured during revolutions 991 and 992 contained energy influxes a factor of three larger, and assuming the same relationship between total energy influx and the intensities of the emissions which Rees calculated for revolution 1108, the column emission rates in the kR range would be obtained. Such intensities were measured by Sandford for $K_p$ of about 3.

Therefore, the electron energy influxes measured by the OGO-4 experiment appear to be sufficiently intense to produce the mantle aurora.

5. Pitch Angle Distributions

Four point pitch angle distributions at the energy 2.3 kev were also obtained from the experiment, and three example distributions measured in the morning hours at the latitude of the mantle aurora are displayed in Figure 11. In general the distributions indicate isotropic distributions of the electron flux over the upper hemisphere.

At this time we do not consider departures from isotropy shown in the figure to be significant because of the difficulty in making these relative measurements with independent detectors. About two weeks after initial turn-on the experiment was beset with some noise problems in the detectors, which worsened with time in orbit. While the analysis of the data involved the subtraction of this noise from the counting rates, with estimates of the accuracy of this background included in the error bars of the plotted points, there remains some uncertainty in the exact values. We are confident, however, that these problems do not affect the general results presented.

6. Spatial Distribution

A preliminary study of the spatial distribution of the precipitation region of 7.3 kev electrons has been performed utilizing about 30 observations of the band region between 06 and 12 hours MLT. In addition to the previous definition of the band region, i.e., the precipitation of 7.3 kev electrons not in coincidence with structured 0.7 kev electron precipitation, an additional criterion was imposed: the flux at 7.3 kev must have exceeded $10^6$ electrons/cm$^2$-sec-ster-kev. Figure 12 contains the average boundaries of this region for two hour intervals between 06 and 12 hours MLT. Assuming the energy spectrums are consistently shaped like spectrum number 1 plotted in Figure 9, this flux at 7.3 kev on the basis of Rees' calculations (Rees, 1970) would correspond to the energy influx which would produce the 0.25 kR contours of Sandford (1968, Figure 3). Therefore, this contour of λ3914 emission is also plotted in Figure 12 for the mantle aurora. Finally in the same figure we have plotted the region of discrete auroral emissions as observed on all-sky camera photographs taken during the IQSY (Stringer and Belon, 1967). These boundaries are based upon the incidence of rayed arcs during 15 minute intervals and are the dominant auroral forms for defining the auroral oval in these morning hours (see also Feldstein, 1963; Lassen, 1967).

While the coincidence between the 7.3 kev electron flux and the λ3914 emissions is not exact, it is clearly apparent that the electron precipitation region is much more closely associated with the mantle aurora than the auroral oval. Exact agreement would not be expected because the optical data were acquired during the southern winter of 1963, whereas the particle measurements were made during the last half of 1967 and the beginning of 1968 from both northern and southern hemisphere passes. In addition, criteria established to define the respective boundaries are not necessary entirely compatible.

On the basis of the following facts: (1) that the electron energy influx is sufficient to produce the optical emissions which Sandford has defined as the mantle aurora; (2) both the electron influx profile and the optical emissions are diffuse in nature; and (3) the regions of precipitation and light emission are reasonably associated spatially, we conclude that the precipitation of these drifting electrons, apparently originating near midnight during substorms, is the cause of the mantle aurora.

## DISCUSSION

If the precipitating electrons which produce the mantle aurora spend their lifetime drifting in local time, the magnetic field lines upon which they existed since their release near midnight must be closed. In fact on the day side it appears that these electrons move on lines of force well within the magnetosphere. Fairfield (1968), in an analysis based upon IMP 1, 2, and 3 magnetic field measurements and the conservation of magnetic flux, obtained the transition latitudes between closed and open field lines. This latitude during the noon hours lay at about 78°, several degrees above the high latitude limit of the precipitating electrons, but at the high latitude extent of the optical emissions. As yet the properties of these mantle aurora electrons have not been investigated at hours earlier than 0600 MLT because of the difficulty in identifying the precipitation region as uniquely associated with drifting electrons rather than with coincident substorm activity. Thus we do not yet have any details of the exact source region at midnight.

If one accepts the lifetime history of the electrons as presented in this paper, then one must also conclude that there is no major source or acceleration mechanism for electrons with energies above about 1 kev during the morning hours at latitudes corresponding to the mantle aurora.

It is also reasonable to conclude that the precipitation mechanism exists during the morning hours independent of magnetic activity at midnight. The observations of precipitation in the late morning hours occur both during the times of activity (revolutions 1242 and 1243, Figure 6; revolution 990, Figure 7; revolutions 2833, 2834 and 2835, Figure 8) and during magnetically quiet times at midnight (revolution 1108, Figure 5; revolutions 1244 and 1245, Figure 6; revolution 993, Figure 7; and revolutions 2836 and 2839, Figure 8). The precipitation apparently occurs when a particle population drifts through an existing phenomenon which causes the precipitation.

The precipitating electrons display two dominant characteristics of the effects of strong pitch angle diffusion:

1) The maximum precipitated flux at 7.3 kev appears to be nearly constant, independent of the substorm or time after the storm. Note in Figures 5 through 8 in the morning hours the maximum flux lay between 2.3 and 4.0 x $10^6$ electrons/cm$^2$-sec-ster-kev. In Figure 6 the maximum flux varied from only 2.6 to 2.9 x $10^6$ electrons/cm$^2$-sec-ster-kev for the four passes which occurred over a time interval of 5 hours. In his

treatment of strong pitch angle diffusion Kennel (1969) states "... the precipitation rate becomes relatively insensitive to the size of the diffusion coefficient", and therefore depends only on the size of the loss cone, so the maximum flux should be constant. A particle diffuses across the loss cone in less than the quarter bounce period, or

$$D_o \; T_B/\alpha_o^2 >> 1$$

where $D_o$ is the diffusion coefficient, $T_B$ the quarter bounce period (about 3 or 4 seconds), and $\alpha_o$ is the size of the loss cone (about $2^o$), so

$$D_o >> \frac{\alpha_o^2}{T_B} \simeq 10^{-3}\,/\text{second}$$

2) The pitch angle distributions of the electrons at the altitude of the satellite and, therefore, over the loss cone, are nearly isotropic (Figure 11). Converting the local pitch angles of the measurements to equatorial pitch angles, the measurements near $10^o$ and $83^o$ convert to $0.2^o$ to $0.3^o$ and $1.5^o$ to $2.1^o$ equatorial pitch angles respectively, depending upon the magnetic field strength at the equator for these lines of force. Again, Kennel (1969) concludes, "the fluxes within the loss cone approach isotropy and become more nearly equal to those outside."

If one assumes the dependence of the diffusion coefficient on pitch angle which Kennel used, $D=D_o \sin^q\alpha \approx D_o \alpha^q$, the condition of isotropy implies q must be positive and less than 2. Using his equation 12 and taking the ratio $h(\alpha_1)/h(\alpha_2) \simeq 1$ for $\alpha_1 = 0.2^o$ and $\alpha_2 = 2^o$ equatorial pitch angles,

$$\sim 1 = 10^{q/2} \quad \frac{I_p\left[\frac{2}{2-q}\left(\frac{\alpha_1^{\;2-q}}{D_o T_B}\right)^{\frac{1}{2}}\right]}{I_p\left[\frac{2}{2-q}\left(\frac{\alpha_2^{\;2-q}}{D_o t_B}\right)\right]}$$

where $p=q/(2-q)$ and $I_p$ is a Bessel function of order p and imaginary argument. The argument of the numerator is always smaller than the argument of the denominator for $q < 2$, and the values of these Bessel functions monotonically increase for all orders p. Therefore, if $q \leq 0$, both $10^{q/2}$ and the ratio of the Bessel functions are less than 1 for all $D_o$, so no solution exists. When $q > 2$ the pitch angle distribution will be isotropic part of the way into the loss core and then will plunge exponentially to zero at $\alpha = 0$. This case is probably eliminated by the observations of isotropy extending to equatorial pitch angles as small as $0.2^o$. Thus we have the conditions on the diffusion process that $D_o \gg 10^{-3}$/sec and $0 < q < 2$.

Strong diffusion has the additional property that the particle lifetime is determined only by the geometric size of the loss region, and therefore is independent upon the source strength or intensity of the reservoir of particles with pitch angles larger than the loss cone pitch angle (Kennel, 1969). The lifetime is then $\tau_m = \frac{2T_B}{\alpha_o^2} \simeq 6 \times 10^3$ sec for $\alpha_o \simeq 2^o$. The apparent time on the basis of the data for the electrons to drift from midnight to noon is of the order of 8 hours, or $3 \times 10^4$ sec, about 5 times longer than the lifetime.

Ignoring the effect of strong diffusion as an acceleration process, this lifetime can be used to estimate the source strength in the midnight region. We assume that the particle population has been depleted by the time the electrons have drifted to noon, since little precipitation occurs in the early afternoon hours. We cannot rule out, of course, the situation where the precipitation mechanism also was absent from these hours. Following the approach of O'Brien (1962) for calculating the time to deplete the particles in a tube of force, ($\tau$),

$$\tau \simeq \frac{0.1\ L^4 J_o}{D\beta}$$

where $J_o$ is the omnidirectional equatorial flux at midnight, D is the rate out of the tube of force, and $\beta = v/c$ then

$$J_o = \frac{D\beta\tau}{0.1\ L^4}$$

Using rough energy fluxes instead of omnidirectional intensities with $D \sim 5$ ergs/cm$^2$ sec, $\beta = 0.15$ for 5 kev electrons, $\tau = 8$ hours, and $L \simeq 10$,

$$J_o \simeq 22\ \text{ergs/cm}^2 - \text{sec}$$

or an energy density of about $0.5 \times 10^{-8}$ ergs/cm$^3$. This is equivalent to the energy density of $\approx 35\gamma$ magnetic field. Since we have not traced the mantle aurora electrons back to the midnight region a comparison between the particle energy density and a measured magnetic field energy density in the source region cannot be made. If the source is in the cusp region (Anderson, 1965), where the magnetic field gradient is large (Fairfield, 1968), the field is capable of holding many times its energy density in trapped particles (Hoffman and Bracken, 1967).

The concept developed in this analysis of the release of electrons from the midnight hours followed by a drift through the morning hours with an encounter with a precipitation mechanism is synonymous with the "drifting rain cloud" model proposed by Pfitzer and Winckler (1969) to account for intensity increases of > 50 kev electrons at the geostationary orbit. Of course, the drift rates of the 7.3 kev electrons are an order of magnitude slower than the rates for the nominally 100 kev electrons (Arnoldy and Chan, 1969).

The region of precipitation of the low energy electrons is somewhat at variance with the pattern described by Akasofu (1969) during the development of a substorm. He indicates that 5 kev electrons appear concentrated in the auroral bulge in the midnight sector and also rapidly expand in local time along the noon hemisphere auroral oval. We would suggest instead that the 5 kev electrons slowly expand through the morning hours following the locus of the >50 kev electrons, rather than move into the noon hemisphere auroral oval. The noon hemisphere auroral oval 5 kev precipitation does not seem to be associated with these substorm released particles.

## SUMMARY OF CONCLUSIONS

While this limited body of data is insufficient to prove a unique connection between the release of a drifting body of electrons in the midnight sector during a substorm and the subsequent precipitation of these electrons in the late morning hours, this sequence of events appears to be the simplest and most reasonable explanation; otherwise the late morning precipitation must be associated with some so far unobserved or not readily observable phenomenon.

We summarize the model proposed for the history of the electrons composing the band region and the conclusions derived from this study:

1. Electrons in the energy range 0.7 kev to 25 kev are released on closed magnetic field lines in the midnight region at the time of magnetospheric substorms.
2. These electrons drift on closed field lines through the morning hours at least as far as noon.
3. The drifting electrons encounter a precipitation mechanism which is present independent of magnetospheric substorm activity.
4. These precipitating electrons can produce the mantle aurora at least during the local times from 06 to 12 hours.
5. This body of precipitating electrons does not produce the aurora in the late morning or early afternoon portion of the auroral oval.
6. No morning or noon energization mechanism for electrons is necessary to account for the mantle aurora.
7. The precipitating electrons display the effects of strong pitch angle diffusion: the diffusion coefficient must be greater than about $10^{-3}$/sec while Kennel's (1969) q must lie between 0 and 2. This range of q's implies that the diffusion mechanism is not highly concentrated either at the equator or at low altitudes.
8. The lifetime of the electrons is about $6 \times 10^3$ sec.

## ACKNOWLEDGMENTS

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## FIGURE CAPTIONS

Figure 1. Data from a northern midnight pass during a magnetically quiet period showing the lack of electron precipitation near midnight at such times. It also gives a baseline in particle fluxes for comparison with the following examples. See text for a general explanation of the content of the figures.

Figure 2. Data during a large and lengthy magnetospheric substorm showing large fluxes of precipitating electrons near midnight, but nothing near noon.

Figure 3. Data during a large and lengthy magnetospheric substorm showing only small fluxes precipitating near noon even five hours after the onset of the storm.

Figure 4. Data during a large magnetospheric substorm showing the lack of precipitating electrons in the early afternoon, but large fluxes in the early evening hours.

Figure 5. Data from a late morning pass showing the presence of precipitating electrons five hours after the end of a substorm near midnight.

Figure 6. Data from a series of four passes showing the electron precipitation in the morning hours five to ten hours after a substorm at midnight.

Figure 7. Data from a series of noon and midnight passes showing decreasing electron precipitation at night coincident with decreasing magnetic activity, but constant electron precipitation at noon. It is argued that the electrons in the noontime precipitation originated during the substorm some eight hours earlier.

Figure 8. Data from a series of morning and post midnight passes showing decreasing electron precipitation at night coincident with decreasing magnetic activity, but continual electron precipitation during the morning hours. It is argued that the electrons in the morning precipitation during revolutions 2833 through 2836 originated from the midnight region during the magnetic activity during midday UT, while that during revolution 2839 originated from the midnight region during the magnetic activity from 20 to 24 hours UT.

Figure 9. Four point energy spectrums of near $10^{o}$ local pitch angle electrons in the region of the mantle aurora.

Figure 10. Energy spectrums of the energy influx calculated from the spectrums in Figure 9 assuming isotropy over the upper hemisphere.

Figure 11. Four point pitch angle distributions at an energy of 2.3 kev in the region of the mantle aurora. The flux for the distribution labeled "3" should be multiplied by 10.

Figure 12. A polar plot of the spatial distribution of the 7.3 kev electron precipitation during the late morning hours in comparison with the region of λ3914 mantle aurora emission (Sandford, 1968) and the auroral oval (Stringer and Belon, 1967).

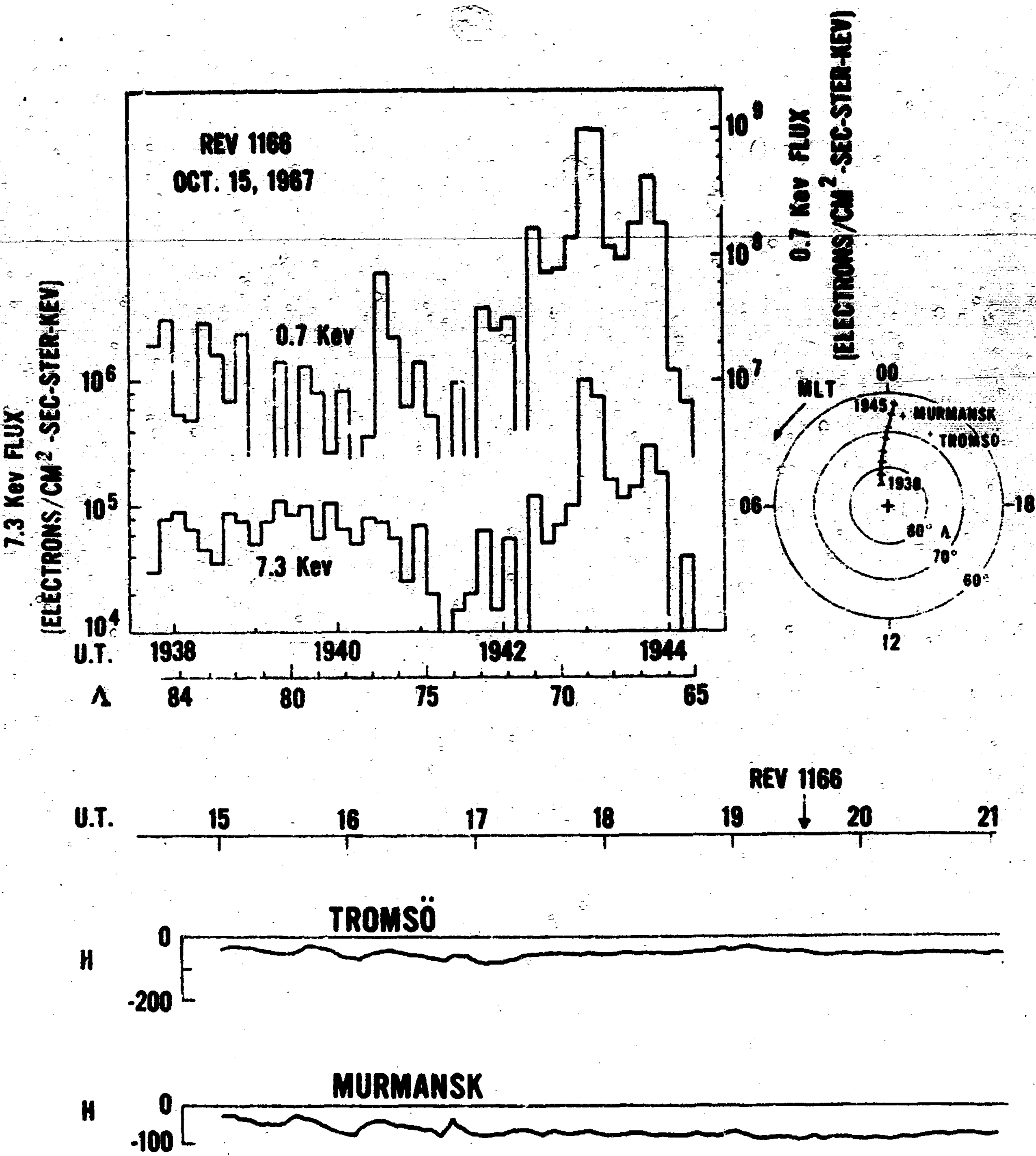

REV 1166
OCT. 15, 1967
0.7 Kev
7.3 Kev
7.3 Kev FLUX
(ELECTRONS/CM² -SEC-STER-KEV)
0.7 Kev FLUX
(ELECTRONS/CM² -SEC-STER-KEV)
U.T.
1938
1940
1942
1944
Λ
84
80
75
70
65
MLT
00
06
18
12
1945
MURMANSK
TROMSO
1938
80° Λ
70°
60°
REV 1166
U.T.
15
16
17
18
19
20
21
TROMSÖ
H
0
-200
MURMANSK
H
0
-100

FIGURE 1

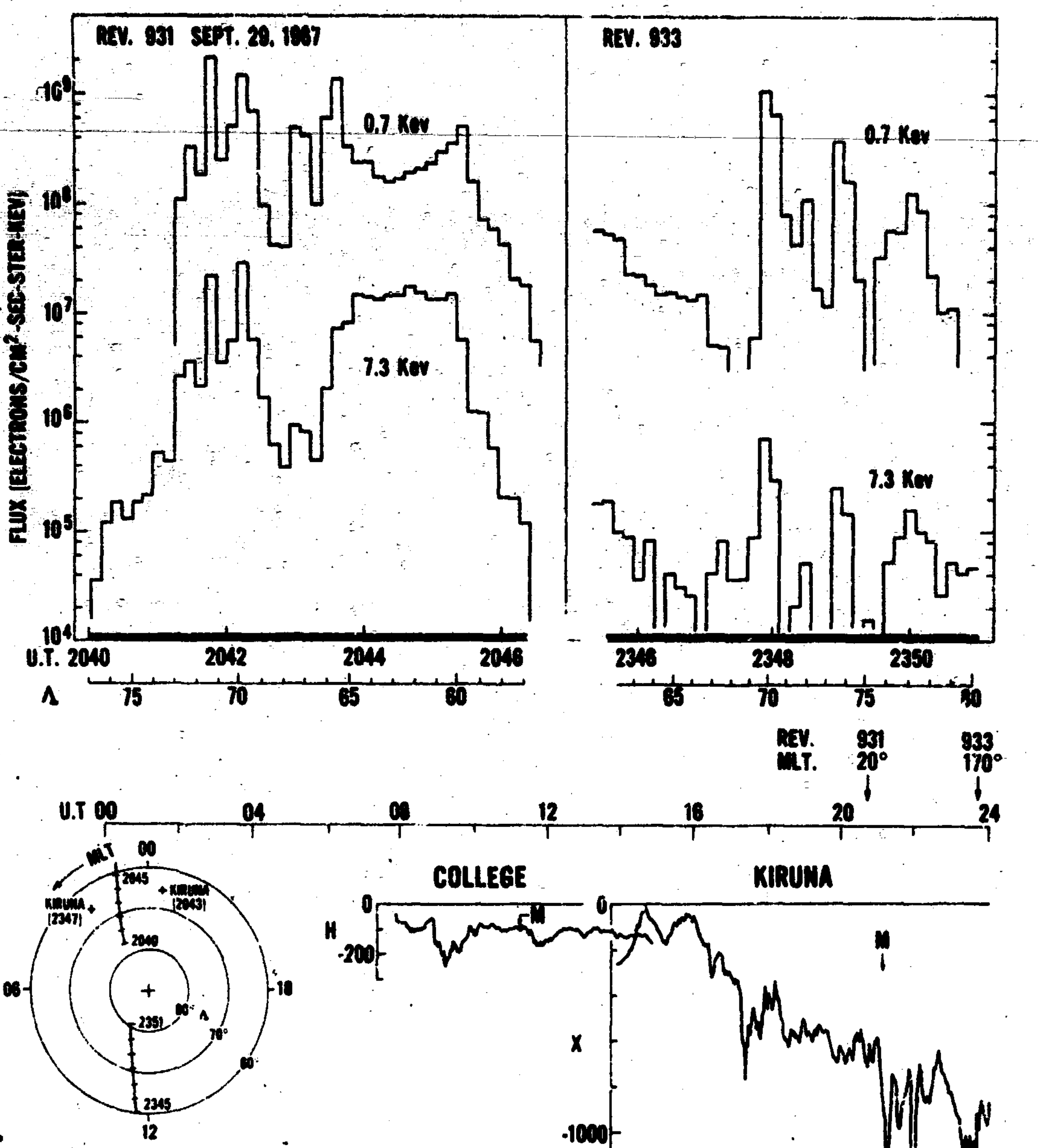
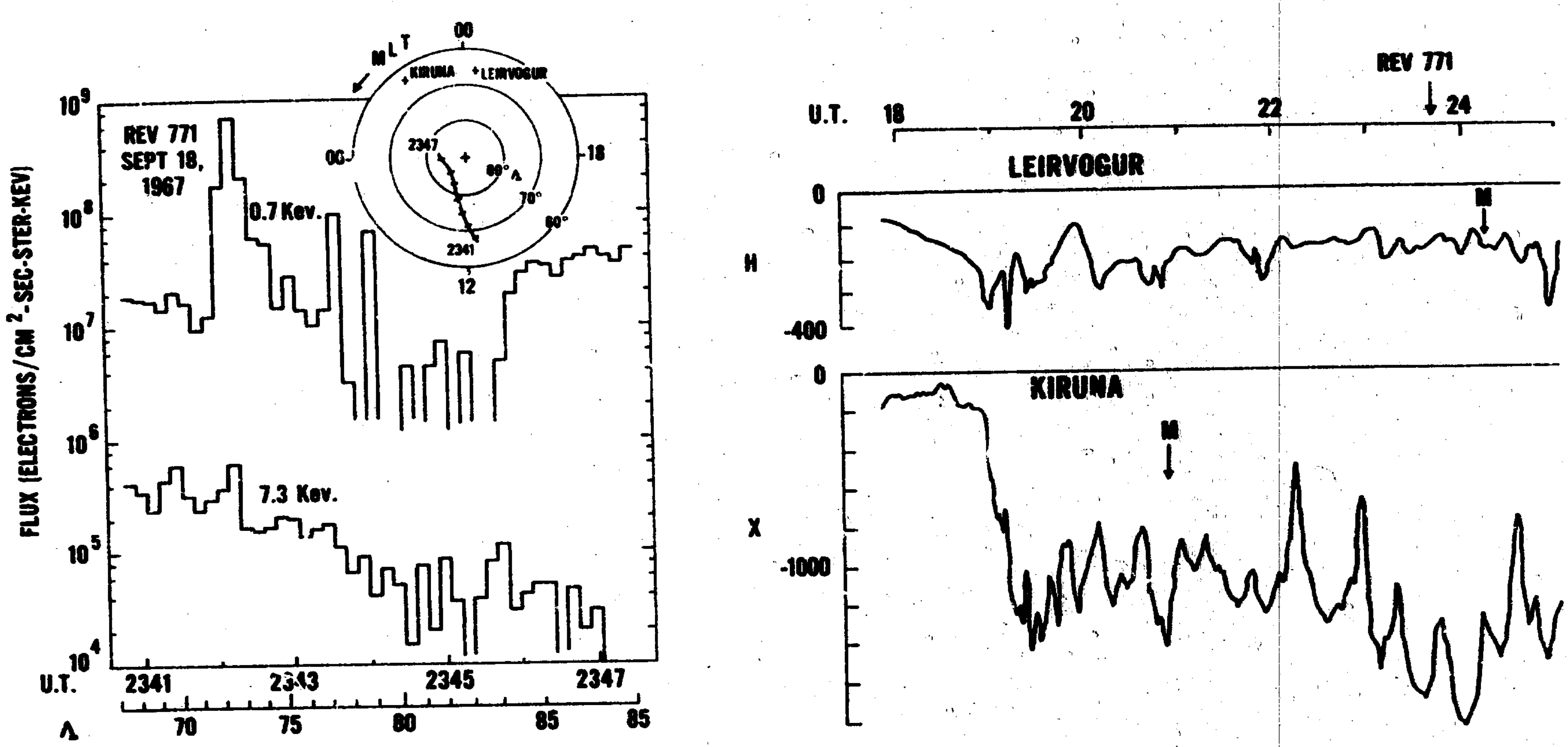
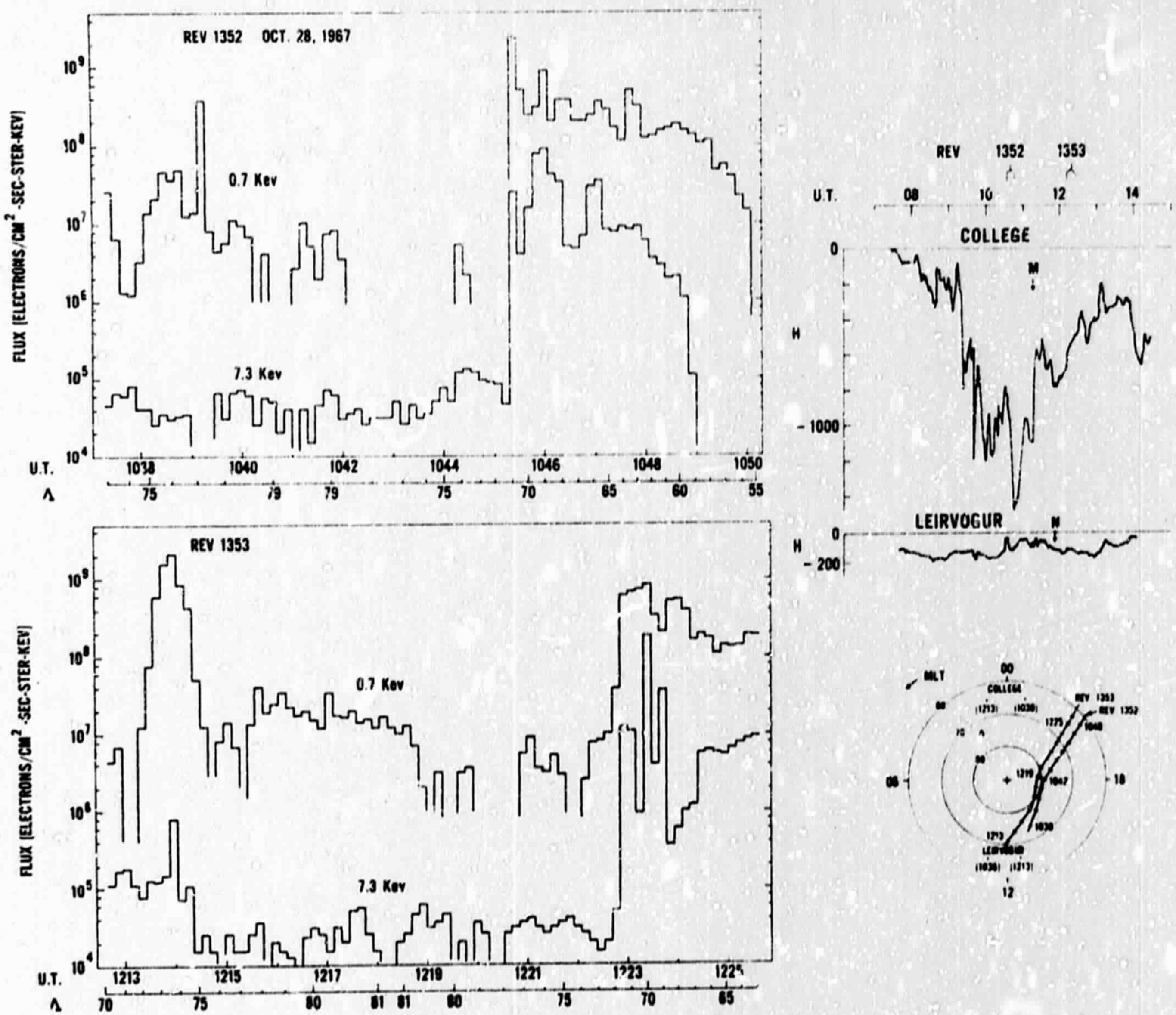

REV. 931 SEPT. 29, 1967
REV. 933
0.7 Kev
7.3 Kev
FLUX (ELECTRONS/CM²-SEC-STER-KEV)
U.T. 2040
2042
2044
2046
2346
2348
2350
REV. 931 933
MLT. 20° 170°
U.T 00
04
08
12
16
20
24
MLT
KIRUNA (2347)
KIRUNA (2043)
COLLEGE
KIRUNA
H
X
-200
-1000

FIGURE 2



REV 771
SEPT 18, 1967
0.7 Kev.
7.3 Kev.
FLUX (ELECTRONS/CM 2-SEC-STER-KEV)
U.T.
2341
2343
2345
2347
Λ
70
75
80
85
85
MLT
00
06
12
18
KIRUNA
LEIRVOGUR
REV 771
U.T.
18
20
22
24
LEIRVOGUR
H
0
-400
M
KIRUNA
X
0
-1000
M


FIGURE 3


REV 1352 OCT. 28, 1967
0.7 Kev
7.3 Kev
FLUX (ELECTRONS/CM$^2$-SEC-STER-KEV)
U.T.
Λ
REV 1353
0.7 Kev
7.3 Kev
FLUX (ELECTRONS/CM$^2$-SEC-STER-KEV)
U.T.
Λ
REV 1352 1353
U.T.
COLLEGE
M
H
-1000
LEIRVOGUR
M
H
-200
MLT
00
06
12
18
COLLEGE
LEIRVOGUR
REV 1353
REV 1352

FIGURE

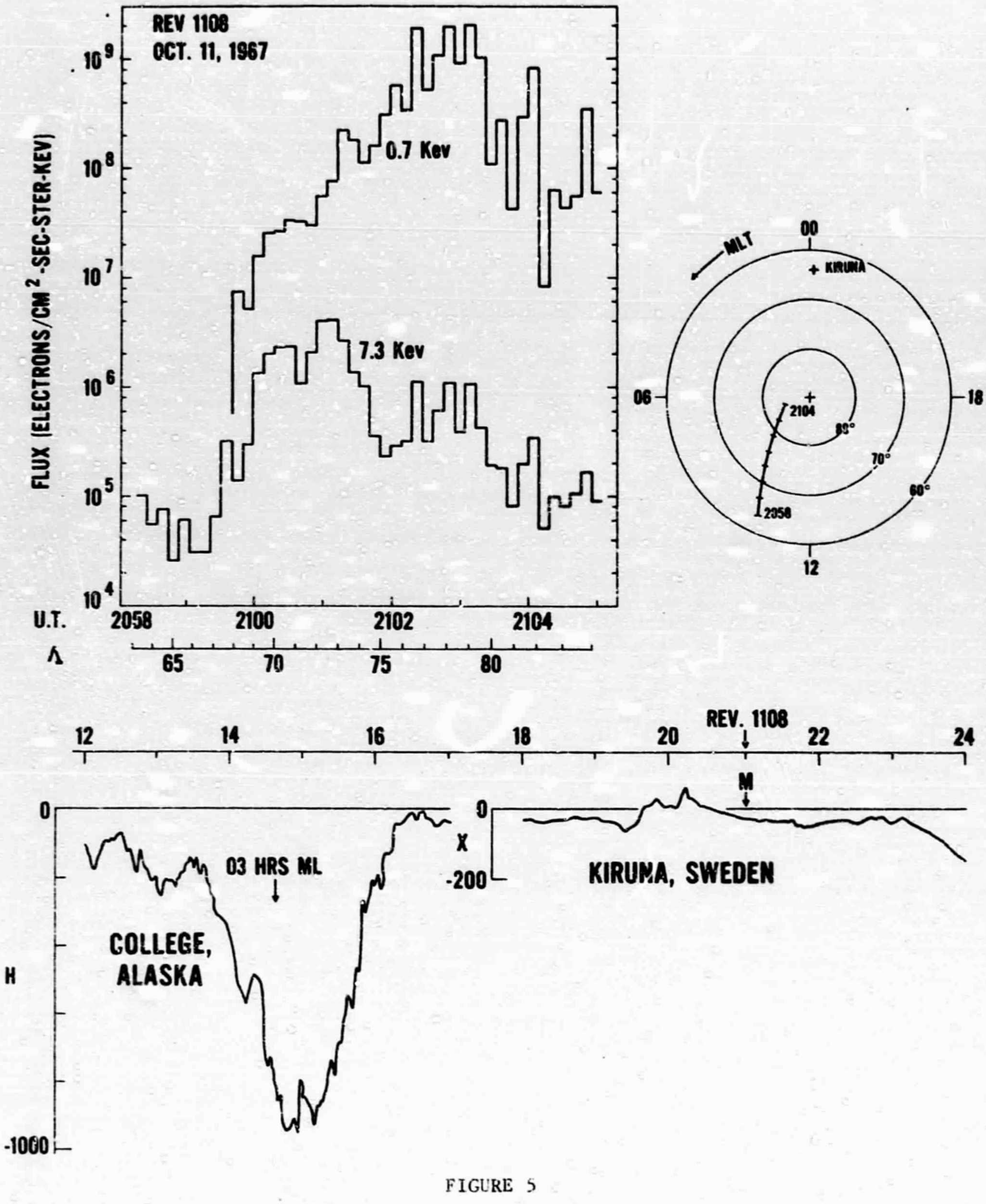

REV 1108
OCT. 11, 1967
FLUX (ELECTRONS/CM 2 -SEC-STER-KEV)
0.7 Kev
7.3 Kev
U.T.
2058
2100
2102
2104
Λ
65
70
75
80
MLT
00
+ KIRUNA
06
18
12
2104
80°
70°
60°
2058
12
14
16
18
20
22
24
REV. 1108
M
0
X
-200
KIRUNA, SWEDEN
03 HRS ML
COLLEGE, ALASKA
H
-1000

FIGURE 5

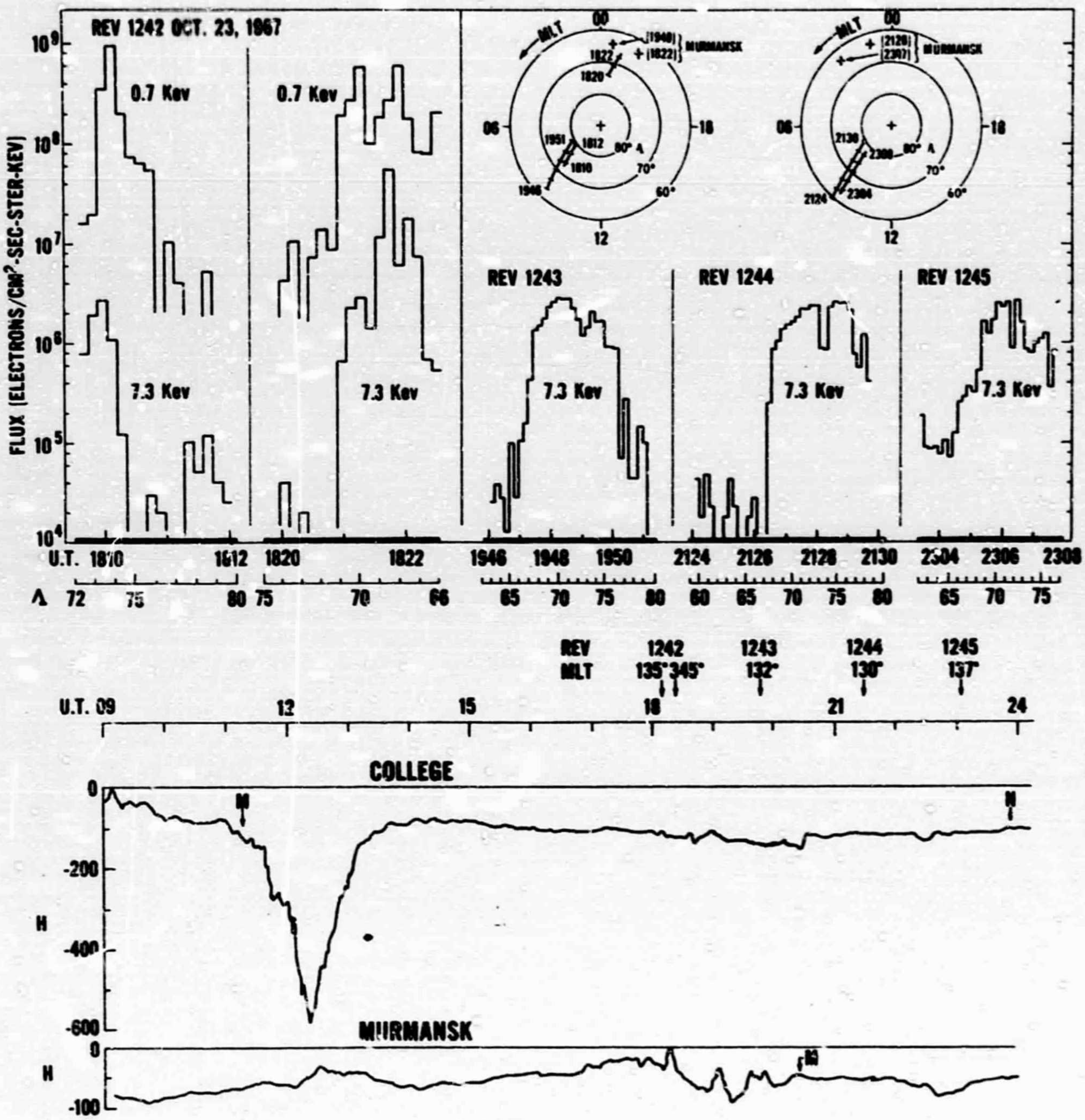
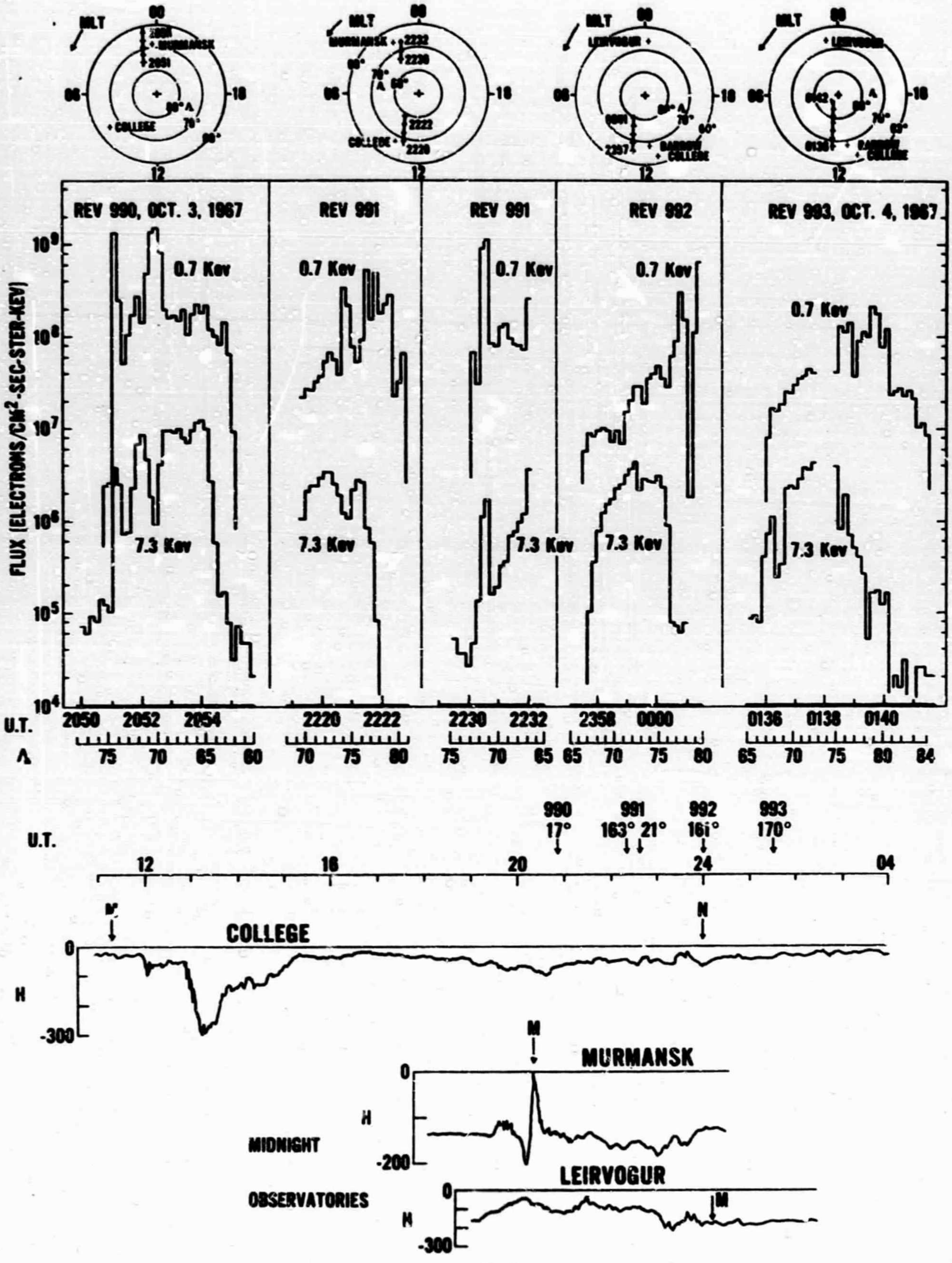

REV 1242 OCT. 23, 1967
0.7 Kev
0.7 Kev
7.3 Kev
7.3 Kev
MLT
MURMANSK
REV 1243
REV 1244
REV 1245
7.3 Kev
7.3 Kev
7.3 Kev
FLUX (ELECTRONS/CM²-SEC-STER-KEV)
U.T.
Λ
REV 1242 1243 1244 1245
MLT 135° 345° 132° 130° 137°
U.T. 09 12 15 18 21 24
COLLEGE
H
MURMANSK
H

FIGURE 6



MLT
00
06
18
12
MURMANSK
COLLEGE
LEIRVOGUR
REV 990, OCT. 3, 1967
REV 991
REV 991
REV 992
REV 993, OCT. 4, 1967
0.7 Kev
7.3 Kev
FLUX (ELECTRONS/CM²-SEC-STER-KEV)
U.T.
Λ
990
17°
991
163° 21°
992
161°
993
170°
COLLEGE
H
-300
MURMANSK
MIDNIGHT
OBSERVATORIES
-200
LEIRVOGUR


FIGURE 7

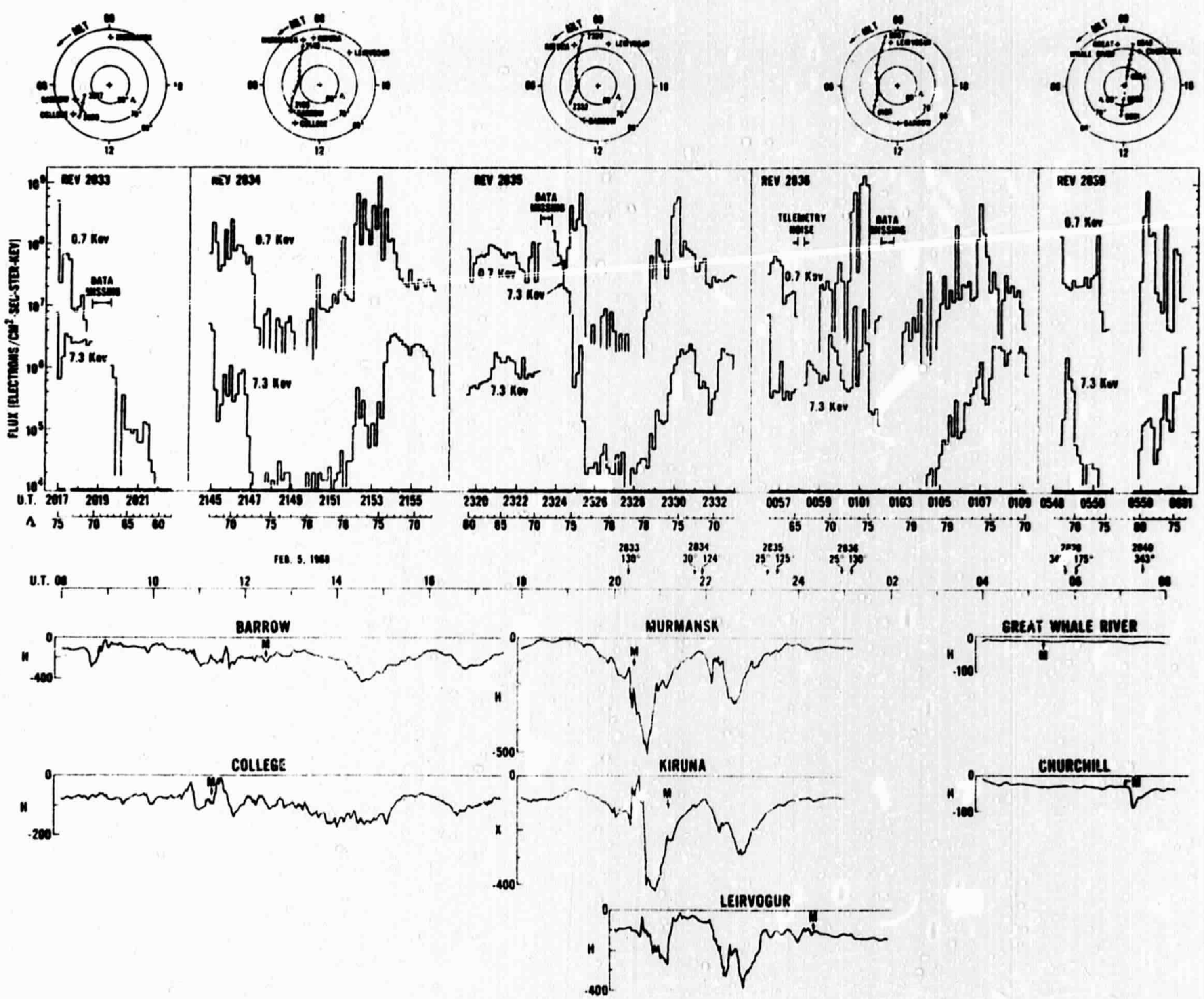

REV 2833
REV 2834
REV 2835
REV 2836
REV 2839
0.7 Kev
7.3 Kev
DATA MISSING
TELEMETRY NOISE
FLUX (ELECTRONS/CM² SEC-STER-KEV)
U.T.
Λ
FEB. 5, 1968
BARROW
COLLEGE
MURMANSK
KIRUNA
LEIRVOGUR
GREAT WHALE RIVER
CHURCHILL

FIGURE 8

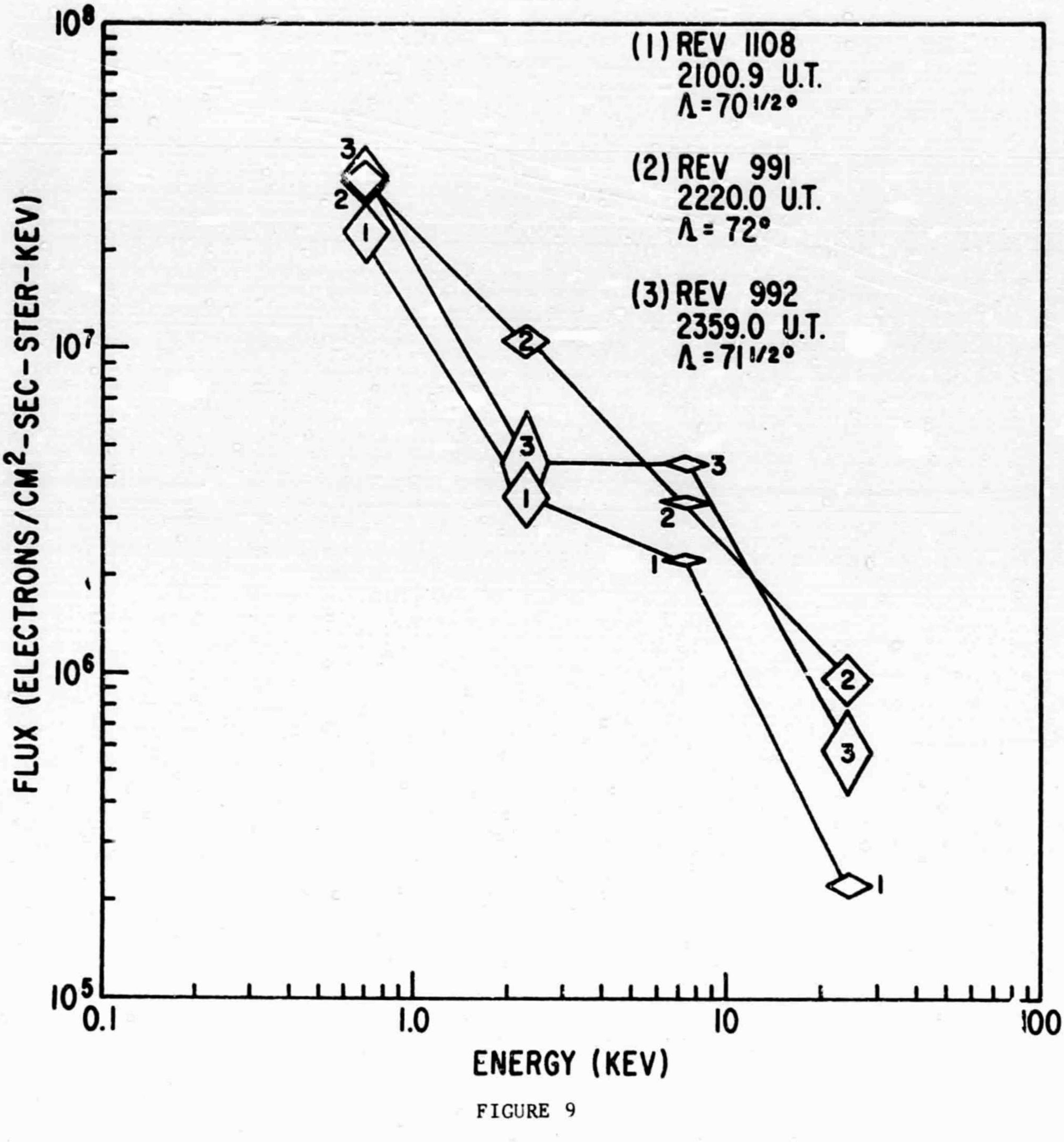

(1) REV 1108
2100.9 U.T.
Λ=70 1/2°
(2) REV 991
2220.0 U.T.
Λ= 72°
(3) REV 992
2359.0 U.T.
Λ=71 1/2°
FLUX (ELECTRONS/CM2-SEC-STER-KEV)
10^8
10^7
10^6
10^5
0.1
1.0
10
100
ENERGY (KEV)

FIGURE 9

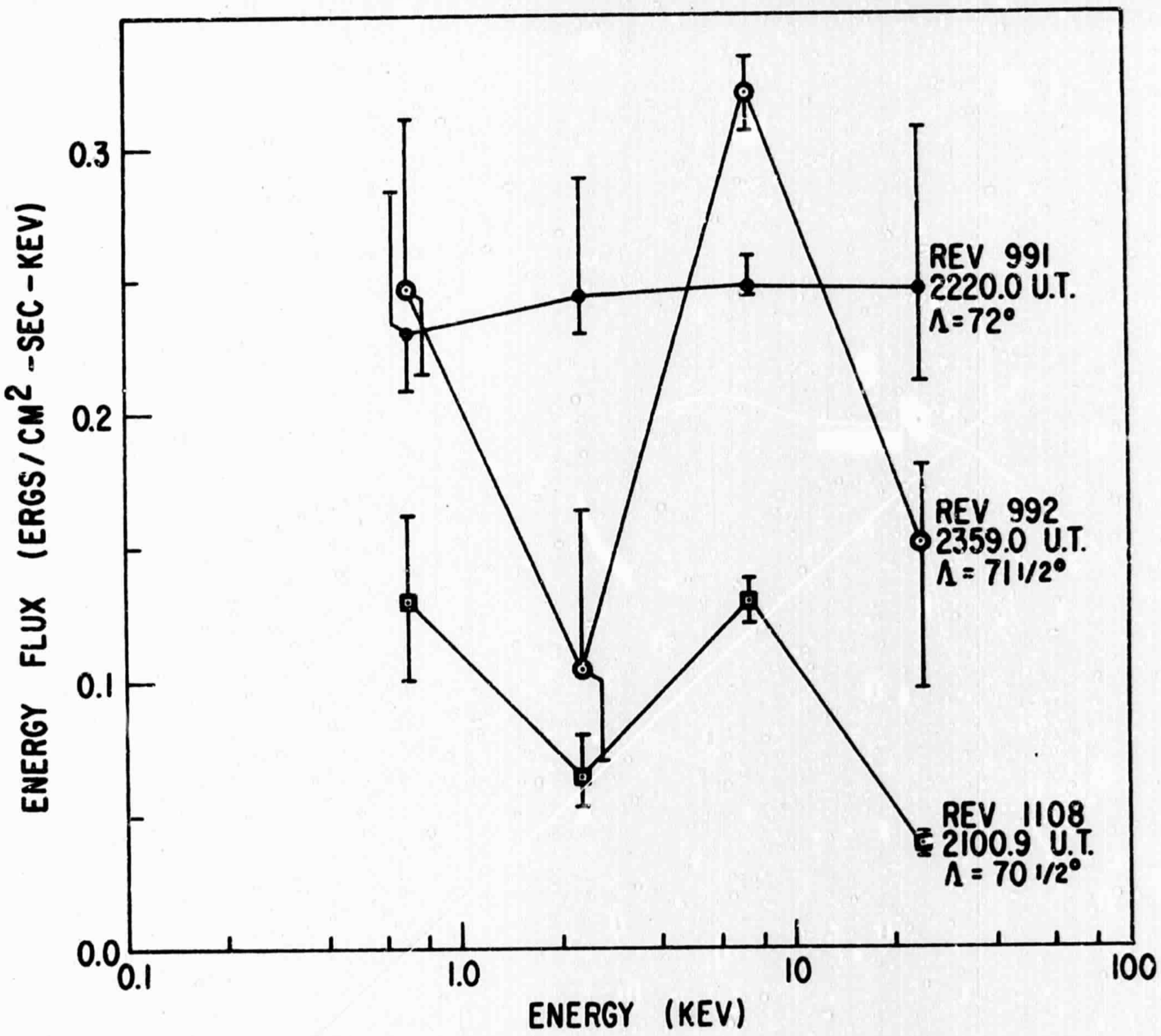
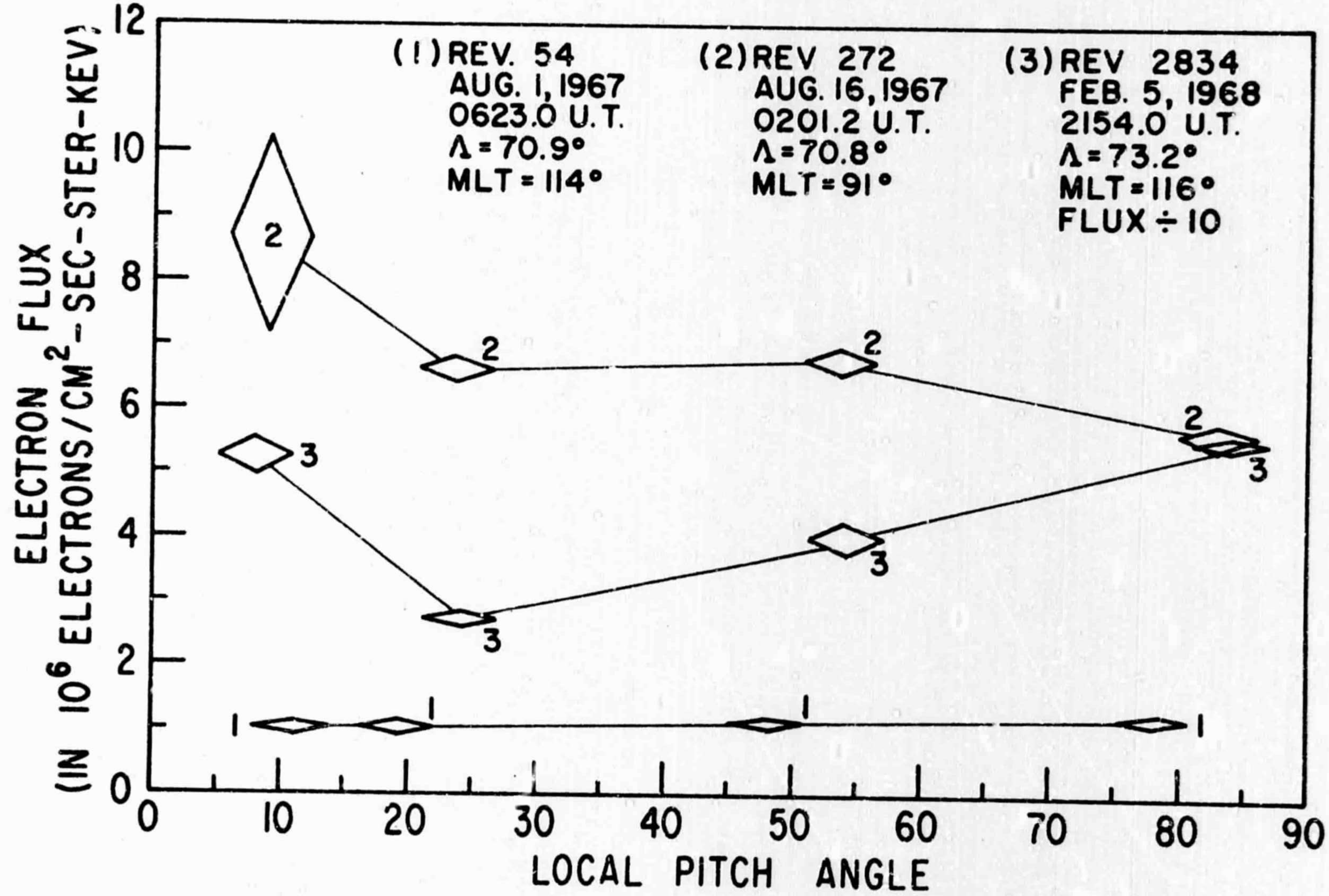

ENERGY FLUX (ERGS/CM2 -SEC-KEV)
0.3
0.2
0.1
0.0
0.1
1.0
10
100
ENERGY (KEV)
REV 991
2220.0 U.T.
Λ=72°
REV 992
2359.0 U.T.
Λ= 71 1/2°
REV 1108
2100.9 U.T.
Λ = 70 1/2°

FIGURE 10



(1) REV. 54
AUG. 1, 1967
0623.0 U.T.
Λ = 70.9°
MLT = 114°
(2) REV 272
AUG. 16, 1967
0201.2 U.T.
Λ = 70.8°
MLT = 91°
(3) REV 2834
FEB. 5, 1968
2154.0 U.T.
Λ = 73.2°
MLT = 116°
FLUX ÷ 10
ELECTRON FLUX
(IN 10^6 ELECTRONS/CM^2 - SEC - STER - KEV)
LOCAL PITCH ANGLE
0
2
4
6
8
10
12
0
10
20
30
40
50
60
70
80
90


FIGURE 11

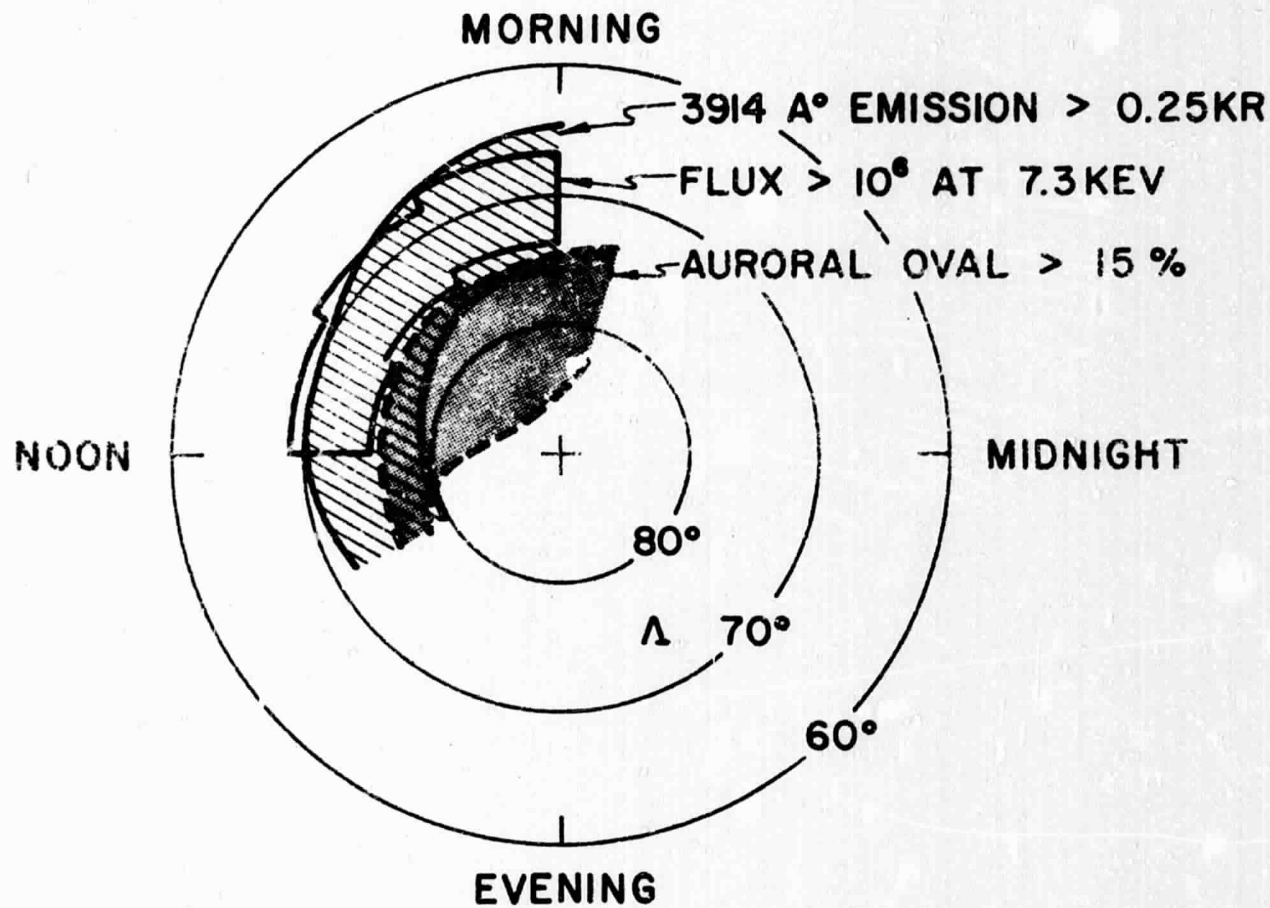

MORNING
3914 A° EMISSION > 0.25KR
FLUX > 10⁶ AT 7.3KEV
AURORAL OVAL > 15 %
NOON
MIDNIGHT
80°
Λ 70°
60°
EVENING

FIGURE 12